Human forces in hands free interaction: a new paradigm for immersive virtual environments

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***Abstract*— A recent trend in virtual environments aims at making the user free of devices or limitations in its motion, at the benefit of immersiveness and interactivity. This work introduces an interaction paradigm that goes beyond motion based interaction, by making use of measured real forces exerted by the user in free space. The sensation of touch with virtual object is obtained by vibrotactile stimulation combining virtual contact information with measured forces. In this way the user has an additional dimension of interactivity at the benefit of immersivity, without incurring in the reduction of sense of presence introduced by grounded haptic interfaces. This paradigm is presented and discussed in particular in the context of a boxing training simulation, as one of the possible application scenarios.**

I. INTRODUCTION

Highly immersive systems provide realistic sensations to the user enabling a complete immersion and collocation in a simulated virtual world. In particular, mixed reality setups allow the user itself to share the space with virtual entities that populates virtual and real worlds. It is however extremely important to guarantee a correct representation of perceptual stimuli as feedback to the users to avoid misalignments between virtual and real worlds. The sensation of immersiveness as well as the coherence of the representation during interaction between real and virtual entities must be achieved. In the specific case of CAVE [3] like structures, where the user is completely surrounded by the virtual simulation, the believability and the immersion of the user should not be broken by external factors, since the embodiment with the virtual scene is essential for perceptual consistence. The user should interact in first person directly. The sense of presence or mediated presence is fundamental to achieve good performances inside a virtual world. Moreover typically, immersive systems are used exclusively with visual and aural feedback that are more immediate and can be represented without loss of coherence and presence.

Many systems and applications however are enabled with haptic feedback. This kind of feedback is usually given through a robotic device that is constantly in contact with the user[6]. Unfortunately this connection between the user and the haptic interface causes an artifact at the perception level and limits the movement of the user inside the device workspace. Another kind of haptic interfaces of recent development employs the encountered paradigm [9], [15]. Encountered haptic interfaces provide hands free interaction to the user rendering more natural contacts without requiring a continuous coupling with the operator. However, both problems of workspace and device's coverage of the visual flow during interaction within the environment cause inconsistence in the perception, resulting in a loss of presence and total immersion by the user.

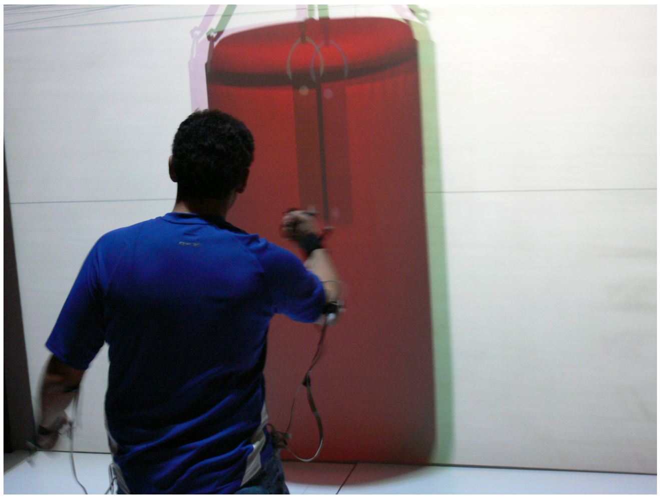

Fig. 1. A session of virtual boxing training

In literature many gloves are proposed for the interaction with 3D worlds. They allow the user to perform movements freely without workspace or posture constraints. Some of them also employs some kind of feedback (as piezoceramic benders [19] or vibrational motors). Starting from the concept of giving the user the capability of moving freely inside the environment, we propose in this paper the adoption of small and cheap vibro-motors to be used as feedback during interaction in virtual worlds. Gloves are not required to exploit this concept and vibrational motors can be applied directly where the stimulus is more efficient for the specific application. However a simple vibrational feedback cannot guarantee that the user will exhibit the exact amount of force needed to perform a particular task. For this reason we improved this paradigm augmenting the vibrational feedback with EMG signals sensor assessing a precise estimation of

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the exerted force. EMG sensors can exactly detect the force applied during the interaction with the virtual world from the activation signals produced by the user's muscles. At the same time the intensity of the feedback can be adjusted depending on the input force.

The rest of the paper is structured as follows. Next section will introduce the state of the art about vibrational feedback and EMG sensing. Section 3 presents the architecture of the proposed system with technical details. Section 4 will present the possible interaction paradigms and as specific case a Boxing training platform will be discussed to validate the usability and show the capabilities of the proposed system. Section 5 presents the conclusions and future works to be done with the proposed system.

II. RELATED WORKS

The integration of human force based on EMG signals in virtual environments has been normally used in the rehabilitation field to control devices and measure the performance in the movement of the users. S.Kousidou et al. [5] performed a robotic approach to task based therapy. The work focused on a robotic exoskeleton operating in a 3D volume used in conjunction with a Virtual Environment rehabilitation suite for training patients in relearning daily motor tasks. EMG recordings were used to show the capacity of the system to mediate the level of assistance. Marcello Mulas et al. [10] performed an experiment with a device for the hand rehabilitation. The system was designed for people who have partially lost the ability to control correctly the hand musculature, for example after a stroke or a spinal cord injury. Based on EMG signals, the system can "understand" the subject evolution to move the hand and thanks to its actuators can help the fingers movement in order to perform the task in virtual environment.

Hideaki Touyama et al. [16] performed a work using the advantages of the EMG signals. It was proposed to use these signals as a promising human interface in immersive multi-screen environments. The user would control virtual objects reflecting the activations of the user's muscles to realize fine operations.

In the real world, when a person touches an object, forces are imposed on the skin. However, this relation between touch and force is not available like a natural link in the Virtual Environments. Haptic interfaces have been applied to solve this problem acting like generator of mechanical impedance. Impedance represents a relationship between forces and displacements in the skin surface and transmits the touching of virtual objects to the human being.

The mechanoreceptors in the skins make humans feel different tactile sensations when touching objects. When object is in touch, these sensations are a combination of tactile primitives like the normal indentation, lateral skin stretch, relative tangential motion and vibration. Different researches have explored the tactile sensation as a modality to present information for orientation and navigation in Virtual Environments. One example is the tactile belts that have been studied by different groups [17], [12] as approaches to provide directions in the horizontal plane to blind people. Lieberman and Breazeal carried out an experiment in real time with a vibrotactile feedback in a Virtual Environment to compensate the movements and accelerate the human motion learning [7]. In the same line of research Bloomfield performed a Virtual Training via Vibrotactile Arrays [1]. Both experiments show a significant improvement in the human cognition and perception.

Following this line of research, one approach of skill acquisition using vibrotactile feedback has been studied by Van Erp and others [4] which performed an experiment to study the intrinsic and extrinsic phenomena involved in the cognitive level when a person move his wrist through the combination of certain vibration stimuli, transmitted by five vibrotactile devices located in specific parts of the forearm and hand of the user. The analysis presented interesting results in the field of motion-vibration in order to know the appropriate locations and combination of vibration stimuli.

In the proposed paradigm we adopted vibrational motors as feedback devices and EMG sensors as input for the force applied during the interaction. The paper presents a full co-located boxing training application to discuss about the proposed paradigm. Next section will detail the interaction paradigm.

III. INTERACTION

During human's interaction inside a virtual environment, whenever the virtual representation of the human body comes in contact with a virtual entity, a collision occurs. The collision affects both the virtual and the real worlds. In a standard paradigm the motion of the user causes the collision, affecting the virtual world and at the same time the virtual world produces a feedback on the user. When the interaction is based on haptic interfaces the user is in contact with the interface itself, allowing to take into account the exerted force. In free-space interaction, instead, only the motion is considered. The proposed interaction paradigm uses the force applied by the user in free-space as a new and fundamental input for interacting with virtual environments.

When the user is acting against an object, a force is recorded by EMG sensors placed on the user's body and during contact this force is used for interacting with virtual objects. From a physical simulation point of view this means that the interaction's force of the user's avatar with an object is not based on its quantity of motion but instead on exact force exerted by the user. The force transmitted from the user in the real environment to the object in virtual environment has a direction along the velocity of impact and a modulus adapted from the real force. This modulus depends on the specific application, for example in the case of boxing training the force values of the biceps and triceps muscles are averaged.

Correspondently, the feedback from the environment to the user is generated by taking into account the exerted force. The result is a vibrotactile stimulus proportional to the instantaneous applied force and the stiffness of the object. This stimulus lasts until there is some compenetration between

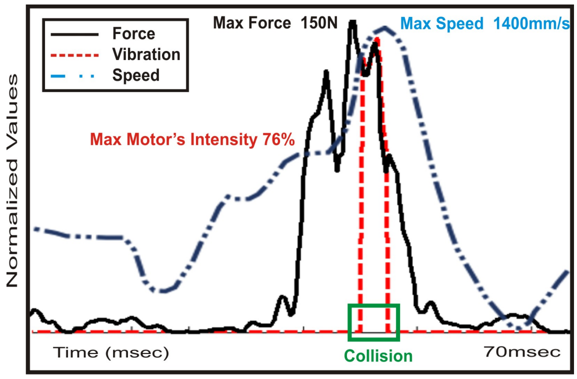

Fig. 2. Correspondence between vibrational stimulus, exerted force and user's movement.

the user's avatar and the virtual object. Figure 2 shows the correspondence between the user's movement, the user force and the vibrational stimulus during a recorded interaction. The plot reports also the maximum values achieved during the interaction.

The proposed system has a wide area of application as target. It's versatility allows the system to be adopted on a large variety of virtual reality application where free interaction is a key factor. A typical situation is one where the user should be able to touch objects in the virtual world and grab as well as move them within the environment to accomplish some specific task. In particular the vibration feedback adds a big perceptual aid to the interaction making possible to understand exactly when a collision occurs[11].

The presented technology is also employable in shape recognition task where objects may be occluded from the user sight. All other applications that need an estimation of the user's applied force benefits from the accurate recording of the EMG capturing system. In particular when the interaction with the scene is mediated by a virtual tool the capacity of the proposed system to detect the exerted force during manipulation is essential. A wide area of VR applications that can adopt this system is the one of medical practice/training where precise measurements of position, acceleration and forces is fundamental. Another specific area is the one involving manual skills and sport activities.

As testing application we decided to present for the purpose a boxing training setup that will be detailed in section V.

IV. ARCHITECTURE OF THE SYSTEM

The system is composed of 3 computers responsible for the graphic rendering, one machine that manages the tracking and several embedded part displaced on the body of the user. Figure 3 depicts a schematic of the parts that comprise the overall system.

A. Vibrational Stimuli

The kinesthetic field plays an important role in the human perception. Although the typical haptic interfaces are able to transmit touching sensations of virtual object to the human being, one important drawback is that the human

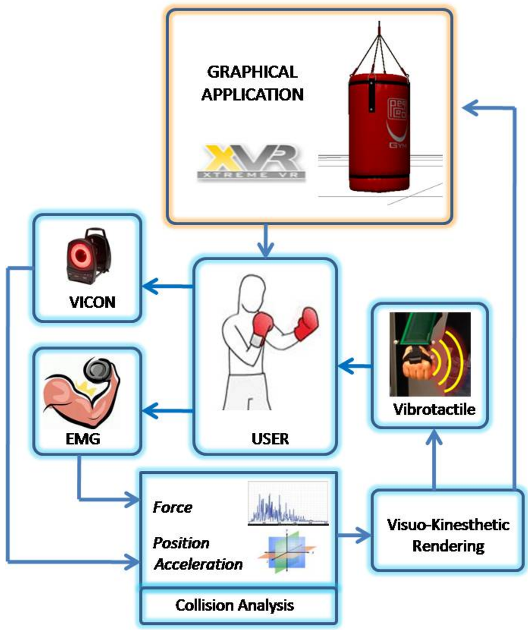

Fig. 3. Architecture of the proposed system

being must be connected to these devices all the time producing a restriction of the movements. Moreover, required specifications in the sport field related to the speed and force are too big for normal haptic interfaces. However, the vibration represents an interesting feedback stimulus that can solve all these limitations problems. This project performs a correlation between force impact and vibration in order to transmit a haptic feed-back that makes the users feel a kinesthetic stimulus proportional to the force applied during the collision.

The vibrotactile control system used in this setup was specially designed to control four vibration motors. In general terms the system consists of one Microchip microcontroller (PIC18F4431) capable to control four PWMs (Pulse Width Modulator) in hardware level with a 12-bit resolution. The power control section uses an IC ULN2803 (Darlington transistors array) which modules the total amount power energy through the PWMs that are applied to the vibration-motors. The communication is based on RS232 protocol which transmits the information given by the computer to the microcontroller. Two vibration motors were attached to the index and the ring fingers of each hand of each user in order to transmit the stimuli in the frontal part of the fist. In a real collision, the kinesthetic perception is proportional to the force applied during the impact. Moreover, an important factor to be considered is that each user can achieve different levels of force depending of his/her physical condition. Therefore it is necessary to normalize and calibrate the vibration system according to the maximum contraction force achieved of each user. The equation used is:

$$I = V_{th} + (SF * PWM_{Max})/MF_{VC} \quad (1)$$

Where I is the actual Intensity factor in bits, SF is the actual

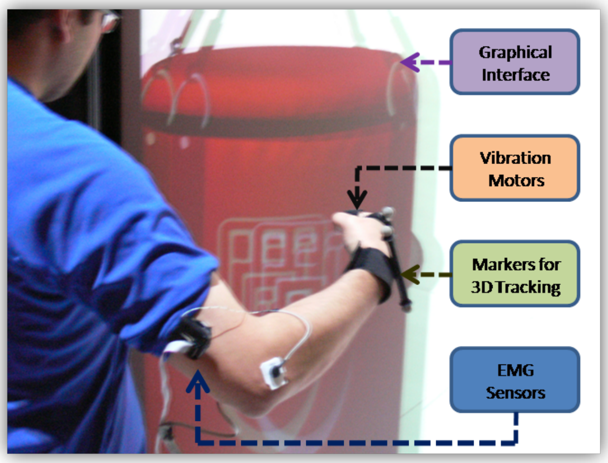

Fig. 4. Multimodal rendering components of the system

force performed by the user's muscles, PWM_{Max} is the maximum range of the PWM (12-bits (4095)) minus V_{th}, MF_{VC} is the maximum force in a Voluntary Contraction obtained by each user(see calibration section). V_{th} is the smallest values of the intensity that can be displayed by the vibrational motors adopted. This formula guarantees that even if the user is not doing a force anyway the contact with the virtual entity is perceived by the user. Following the equation 1 the system is able to modulate the PWMs from 0 to 4095 (min-max) controlling in a proportional way the intensity of the vibration motors.

B. EMG Sensors

1) EMG Description: The EMG signal is a biomedical signal that measures electrical currents generated in muscles during their contraction. These signals are complex to acquire and process, because they are small (0 to 10mV) and highly susceptible to noise. Normally, a sampling frequency from 2 to 4 KHz should be performed in order to obtain good parameters in the behavior and spectrum of the signal. Therefore, a big drawback is the considerable amount of data that is obtained during the acquisition process of the raw signal using many sensors. A new embedded system capable to perform diverse embedded calculus in real time in order to save computing-time and avoid saturation in the transmission with the raw signals was designed. The main objective of this device is to process, calculate and transmit three important parameters related to muscles: Muscular Time Activation, Force Intensity and Frequency Analysis instead of the raw signals.

2) EMG System: This EMG system consists of two modules: The sensors and the Digital Signal Processing System. On one hand, the sensors attached to the muscles of the human being use in the first phase of amplification an instrumentation amplifier INA121 (specially designed for the use in biomedical signals) that amplifies the signal 500 times the difference in voltage of two EMG electrodes (Ag/AgCl) (Placed on the skin at 2.5cm of distance between them with a gel-skin contact area of $1cm^2$ for each electrode). An active 4th order high-pass filter (10-400Hz) eliminates the noise at low and high frequencies and performs a second amplification that can be chosen by the user varying from 1 to 5 times. The signal passes to an ADC AD7683 16-bits resolution and finally the 2 bytes of information at 4 KHz sampling rate are sent to the Digital Signal Processing System via SPI protocol.

The Digital Signal Processing System is controlled by a Microchip DSPic30F4012 device which performs three important routines: a) Voltage reference and noise level detection, b)Static Calibration (correlation EMG - Force), c) Double Threshold Methodology in Real-time. The detection of discrete events in the EMG is an important parameter in the analysis of the motor system. Therefore, it is essential to apply special methodologies for the correct retrieval of information due to the stochastic and noisy characteristics of the EMG signals. The estimation of on-off timing of human skeletal muscles plays an important role in the EMG analysis. There are different techniques referred to as "'single-threshold methods" which are based on the comparison of the rectified raw signals and an amplitude threshold whose value depends on the mean power of the background noise. However this methodology is not efficient because it does not take into consideration involuntary contraction of the muscles, that normally happens in short time lapses of 30msec. Therefore "'double threshold method" is applied in order to verify the level of noise and the period of time of activation of the contraction.

The Digital Signal Processing System has the objective to acquire the signals from the sensors at 4Khz. The signals are full-wave rectified and enveloped using a Digital fourth-order Butterworth low pass filter with a cut off frequency of 5Hz. The time activation detection process is carried out using a sliding window of 50msec which performs the analysis of the whole signal in order to detect events of signals smaller than 30msec which are considered to be part of individual MUAP(Motor Unit Action Potential) contraction or a noise introduced in the signal.

3) Calibration and Relationship of EMG and Force: There have been a number of studies on the relationship between the EMG and force. Recent research showed that the EMG and force have a linear relationship regardless of the arm posture and the muscle length [13], [18]. Based on these analyses, this study establishes a direct quantification in the relationship between the EMG and the force.

Since the EMG signals have particular specifications for each person, the EMG activity requires to be calibrated in order to correlate this activity with a corresponding force level. A static calibration was carried out through MVC (Maximum voluntary contraction) of each user. The static calibration routines are normally performed making a person lift a determined weight in a determined position depending on the muscle to study. In this experiment the most representative muscles for boxing movements are the biceps and triceps. Therefore the user must perform two gym exercises. For the bicep calibration the movement is called "Curl" where the user holds a dumbbell (2 Kg) in a hand with arms hanging down and the palms of the hands facing the body: the user bends the elbow rotating the palm up before the forearm reaches an horizontal position. For the triceps brachii the user performs a movement called "One-arm dumbbell triceps extension" when the user grips the dumbbell (2 Kg) in one hand with the arm vertical then bends the elbow to lower the dumbbell behind the head to the neck and return to the initial position. Digital Signal Processing System obtains the EMG intensity values during these exercises and performs the correlation between the force to lift a 2 Kg weight and EMG intensity.

C. Tracking and Motion Capture

In mixed and interactive virtual reality systems the use of tracking technology is fundamental. It is a key issue for localization of entities and for proper display of the environment to the observer. In our setup a system with 8 infrared sensible cameras was employed (OMG's VICON MX200)[1]. This system adopts retro-reflective material applied on simple spherical markers to recognize geometries positions and orientations. In particular the head of the user is tracked with markers being placed on special INFITEC[2] stereoscopic glasses. This is necessary for the generation of a correct perspective for the user.

In our setup in addition to the head tracking and especially for interaction purposes two more subjects are captured and constantly monitored: the user's hands. In this way is possible to figure out the movement of the user in real-time. The system works with a frequency up to 300hz and has a spatial resolution under the millimeter.

D. Graphic Display System

The interaction has been carried out in a L-shaped system comprised of two big screens: one frontal and the other lying under the user as a walkable floor. The system is supported by the aforementioned tracking system and four projectors. Each couple of projectors is responsible for the display of one of the screen. Mounted on the lens there are special INFITEC filters that are necessary to decouple the projected images into two separate images in order to make the user feel a stereoscopic experience. All the graphic and scene management was developed through the XVR platform [2] with simple S3D scripts. The synchronization between the different machines that compose the system is granted by a special module of network rendering [8] usable with XVR.

V. Boxing Training Application

The human being has the capacity to transform the biochemical energy in movement. In a traditional analysis $F = ma$, where the force of the hit is equal to the equivalent mass of boxer in the point of contact per the acceleration achieved. That is the reason because in the Boxing exist diverse categories and divisions. The variation of the mass implicates a bigger force/power of the hit. The weight of the

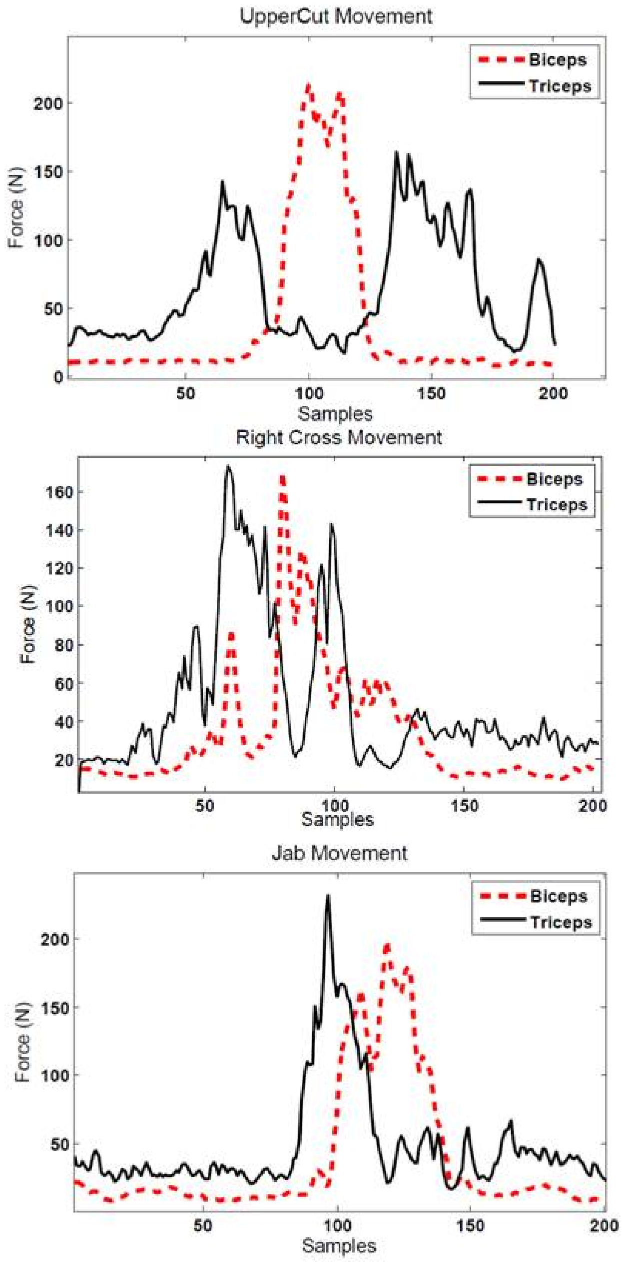

Fig. 5. Force profiles captured by the EMG sensors for each fist

person is determinant; however the acceleration constitutes an advantage for the people that are not heavy. If the user need to increment the force, then he/she should accelerate his/her movements and gain weight or muscular volume, to augment the mass. The power of the hit is calculated by:

$$Power = Force(arm\ mass)\frac{distance\,of application}{\Delta t}$$

The power is the result of the rapid application of the force between the elapsed time. Thus, to hit in a powerful way, the boxer should augment the force, augment the capacity of acceleration, reduce the impact time and reduce the distance of application. In particular it is possible to distinguish several moves/moving patterns:

[1] http://www.vicon.com
[2] http://www.infitech.net

Fig. 6. Screenshot of the boxing bag and schematic of the virtual coupling

- **The jab** is a punch performed by a straight strike from the left hand towards the opponents head.
- **Right cross** is performed when the jab passes over users shoulder and strike the users right hand on opponents jaw.
- **The uppercut**. It is performed with an upwards swipe, landing underneath the opponents chin, users forearm should make a 90 degree angle with the upper arm. The palm of the fist should be facing upwards and the uppercut should knock the opponents head back.
- **The hook** is a semi-circular punch thrown with the lead hand to the side of the opponent's head.

The example application chosen to show the potential of the proposed system is a boxing training that represents a typical training exercise. In literature the only recent attempt with boxing and virtual reality was made by Sidharta and Cruz-Neira in [14]. Unfortunately this work treat the boxing more as a game than as a sport and not analyzes training accelerators and benefits.

In our setup the boxer should hit a suspended boxing bag of heavy weight. The simulation displays a realistic experience both from the graphical aspect and from the physical one. The environment presents a full boxing bag mesh rendered with parallax mapping applying both a normal and an height map to the texture to display a bump effect on the materials of the bag. The physical simulation was developed using the PhysX engine by NVIDIA [3].

The bag is attached with chains and a rope to the ceiling and is free to oscillate and react to the fists of the user. Figure 6 represents a full gym graphic environment where the boxing bag lies. It also shows the spring-dumper system for the virtual coupling between the fist of the user and a virtual sphere that represents the fist as virtual entity inside the simulation. This coupling is used to generate a smoothed trajectory and to assure the stability of the physical simulation.

[3]http://www.nvidia.it/object/nvidia_physix_it.html

For the vibration feedback and signal analysis we applied the concept previously detailed. The contact with the bag is realistic and it is possible to perform the training and to have an exact perception of the interaction also with closed eyes. For the training the application has the facility to record all the movement and performances of athletes and it is possible to show the results of the current training session to motivate the trainee during the exercises. Even if it is a virtual Boxing training the fatigue is present as if the training was real cause the user must activate really his muscles to have good performance responses.

In particular the system is able to distinguish all the kind of attack from the force profiles of the muscles so that is possible to ask to the boxer to perform specific combos within a peculiar rhythm and timing. Figure 5 shows the force profiles for each kind of attack.

VI. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

The paper propose a flexible and not constraining system to display correct kinesthetic feedback to the user during the interaction with virtual worlds. In particular the system can be adopted in several contexts due to its versatility and allows the user to move freely inside a VR/MR environment. The perceptual discrepancies that are present with classic haptic interfaces are solved and the use of EMG sensors guarantee that the forces are properly displayed. This is extremely important to preserve the sense of presence and the immersion into the virtual world. A virtual boxing training application has been developed to show the capability of the system. In particular, it is shown that the precise measurements given by the EMG sensors can enhance the interaction and contributes to the realism of the simulation.

B. Future Works

The interaction paradigm proposed can be employed in several virtual applications. The work will continue investigating interaction modalities with other kind of simulation similar to the boxing training one. In the field of sports training it is interesting to investigate modalities of virtual training and performances gained with respect to real world training. In applications not related to sports, it is however interesting to check improvements on user performances gained through the proposed system. A future research will be focused on multi user interaction and mediated contact between users and virtual entities. In particular the paradigm of one single point of contact used in the boxing training(the fist of the user was represented by a virtual sphere) will be extended to study multiple points of contact/feedback. Similarly, augmenting the number of EMG sensors, it will be possible to achieve a complete biomechanic representation of human movements.

VII. ACKNOWLEDGMENTS

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